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THE OPTICAL FLARE AND AFTERGLOW LIGHT CURVE OF GRB 050904 AT REDSHIFT $z = 6.29$

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ABSTRACT

GRB 050904 is very interesting, since it is by far the most distant gamma-ray burst event known to date ($z = 6.29$). It was reported that during the prompt high-energy emission phase, a very bright optical flare was detected that was temporally coincident with an X-ray flare. Here we use two models to explain the optical flare. One is the "late internal shock model," in which the optical flare is produced by the synchrotron radiation of the electrons accelerated by the late internal shock and the X-ray flare is produced by the synchrotron self-Compton mechanism. The other is the external forward-reverse shock model, in which the optical flare is from the reverse-shock emission and the X-ray flare is attributed to the activity of the central engine. We show that with the proper parameters, a bright optical flare can appear in either model. We think that the late internal shock model is more favored, since in this model the optical flash and the X-ray flare have the same origin, which provides a natural explanation of their temporal coincidence. In the forward-reverse shock scenario, fits to the optical flare and the late afterglow suggest that the physical parameters of the reverse shock are much different from those of the forward shock, as found in previous modeling of the optical flash of GRB 990123.

Subject headings: gamma rays: bursts — ISM: jets and outflows — radiation mechanisms: nonthermal

Online material: color figure

1. INTRODUCTION

Gamma-ray bursts (GRBs) are bright flashes of high-energy photons usually lasting about several seconds. They are by far the most luminous objects in the universe, emitting such large amounts of energy (up to 10^{53} ergs) that they can be detected to very high redshifts ($z > 5$).

GRB 050904 was detected by the Burst Alert Telescope (BAT) on board *Swift* on 2005 September 4 at 01:51:44 UT (Cummings et al. 2005). It was a long (duration $\lesssim 500$ s in BAT), multipeaked, bright burst; the 15–150 keV fluence was $(5.4 \pm 0.2) \times 10^{-6}$ ergs cm^{-2}, and the spectrum can be described by a power law with a photon index of approximately -1.34. Its redshift, which has been measured by several groups (Haislip et al. 2005; Antonelli et al. 2005; Price et al. 2005), $z = 6.29$, makes it by far the most distant GRB discovered to date.

Boër et al. (2005) reported that they detected a very bright optical flare during the prompt high-energy emission phase, and at the same time there was an X-ray flare. It is widely believed that the reverse-shock synchrotron radiation usually peaks in the optical/IR band, and this emission mechanism has been successfully used to interpret the early optical emission from GRB 990123 (Akerlof et al. 1999; Sari & Piran 1999; Wang et al. 2000; Fan et al. 2002; Zhang et al. 2003; Nakar & Piran 2005), GRB 021211 (Fox et al. 2003; Li et al. 2003; Wei 2003; Kumar & Panaitescu 2003), GRB 041219a (Blake et al. 2005; Fan et al. 2005b), and GRB 050525a (Shao & Dai 2005; Blustin et al. 2006). However, in the reverse-shock model it is expected that the emission will make a negligible contribution in the X-ray band (but see Fan & Wei 2005). A strong optical flare accompanying an X-ray flare may also be accounted for by the "late internal shock model" (Fan & Wei 2005). Originally, that model was proposed to interpret the X-ray flare detected in GRB 011121 (Piro et al. 2005) and many *Swift* X-Ray Telescope (XRT) flares (Burrows et al. 2005; Zhang et al. 2005; Nousek et al. 2006).

The optical afterglow light curve of GRB 050904 cannot be described by a simple power law: between ∼3 hr and 0.5 days after the burst, the fading of the afterglow can be described by a power law with index -1.36, but after this time the light curve flattens to a temporal index of -0.82 (Haislip et al. 2005). Tagliaferri et al. (2005) have found a break in the light curve at $t_b \simeq 2.6$ days, which may be a jet effect. In this Letter, we try to explain the optical flare with two models—the reverse-shock emission and the late internal shock model—and then we fit the afterglow light curve including energy injection and jet effects.

2. EXPLANATION OF THE OPTICAL FLARE

2.1. *The Late Internal Shock Model*

In the standard shock scenario, the prompt gamma-ray emission is produced by the internal shock, and the burst duration is determined by the timescale of the central engine's activity. However, some authors have suggested that the activity of the central engine may be much longer than the GRB duration, which could give rise to some signatures in multiwavelength afterglows (Dai & Lu 1998; Zhang & Mészáros 2001; Granot et al. 2003; Ioka et al. 2005). Furthermore, it has been proposed that the iron line observed in some GRB X-ray afterglows is produced by late-time energy injection (Rees & Mészáros 2000; Gao & Wei 2005).

Fan & Wei (2005) first proposed the late internal shock model to account for the bright X-ray flares detected in many GRBs. Here we will show that the late internal shock model can produce not only the X-ray flare but also the optical flare, with the proper parameters.

Following Fan & Wei (2005), the typical synchrotron radiation frequency can be estimated as

$$\nu_m \approx 8.5 \times 10^{15} \left(\frac{\epsilon_e}{0.4}\right)^2 \epsilon_{B,-2}^{1/2} (\Gamma_{\rm sh} - 1)^{5/2} \Gamma_{\rm sh}^{1/2} L_{m,52}^{1/2} \Gamma_2^{-2} \delta t_1^{-1}\ \mathrm{Hz}, \tag{1}$$

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where L_m is the outflow luminosity, $\Gamma_{\rm sh}$ is the Lorentz factor of the internal shock, Γ is the Lorentz factor of the emitting shell, δt is the observed typical variability timescale, and ϵ_B and ϵ_e are the energy fractions occupied by the magnetic field and by electrons, respectively. The convention $Q_x = Q/10^x$ has been adopted, in cgs units, throughout the text.

The cooling Lorentz factor is $\gamma_{e,c} \simeq 7.7 \times 10^8(1+z)/[(1+Y)\Gamma B^2 \delta t]$, where $Y = [-1 + (1+4x\epsilon_e/\epsilon_B)^{1/2}]/2$ is the Compton parameter, with $x \simeq \min\{1, (\nu_m/\nu_c)^{(p-2)/2}\}$ (Sari & Esin 2001). Then the cooling frequency is

$$\nu_c \approx 1.6 \times 10^{11} \left(\frac{1+z}{7.29}\right)^{-2} \times \epsilon_B^{-3/2}[\Gamma_{\rm sh}(\Gamma_{\rm sh}-1)]^{-3/2} L_{m,52}^{-3/2} \Gamma_2^8 \delta t_1 (1+Y)^{-2}\ {\rm Hz}. \quad (2)$$

The synchrotron self-absorption frequency is about

$$\nu_a \approx 2.9 \times 10^{14} \left(\frac{1+z}{7.29}\right)^{-2/7} \times \epsilon_{B,-2}^{1/14}[\Gamma_{\rm sh}(\Gamma_{\rm sh}-1)]^{1/14} L_{m,52}^{1/14} L_{{\rm syn},50}^{2/7} \Gamma_2^{-8/7} \delta t_1^{-5/7}\ {\rm Hz} \quad (3)$$

(Li & Song 2004; Fan & Wei 2005), where $L_{\rm syn}$ is the synchrotron radiation luminosity. The maximum flux of synchrotron radiation is $F_{\max} \approx 3\sqrt{3}\Phi_p(1+z)N_e m_e c^2 \sigma_{\rm T}\Gamma B/(32\pi^2 q_e D_L^2)$, where q_e is the electronic charge, $N_e = L_m\,\delta t/[(1+z)\Gamma m_p c^2$ is the total number of emitting electrons, and Φ_p is a function of p; for $p = 2.5$, $\Phi_p \simeq 0.6$ (Wijers & Galama 1999). D_L is the luminosity distance, and we adopt $(\Omega_M, \Omega_\Lambda, h) = (0.3, 0.7, 0.71)$. Then, for the case $\nu_c < \nu_a < \nu_{\rm obs} < \nu_m$, the observed flux at frequency $\nu_{\rm obs}$ should be

$$F_\nu \approx 100 \left(\frac{\nu_{\rm obs}}{3 \times 10^{14}\ {\rm Hz}}\right)^{-1/2} L_{m,52}^{3/4} \Gamma_2 \epsilon_{B,-2}^{-1/4} \times [\Gamma_{\rm sh}(\Gamma_{\rm sh}-1)]^{-1/4} D_{L,29.3}^{-2} \delta t_1^{1/2} (1+Y)^{-1}\ {\rm mJy}. \quad (4)$$

Now we turn to the observation. Boër et al. (2005) reported that they detected a bright optical flare at frequency $\nu_{\rm obs} = 3 \times 10^{14}$ Hz with a peak flux of 48 mJy. Meanwhile, the *Swift* XRT data show that there is also a peak in the X-ray light curve at nearly the same time as the optical flare, which suggests that the optical flare and the X-ray peak may have the same origin. The slope of the X-ray spectrum is about $-\frac{1}{2}$, and the flux at 1 keV is about 0.08 mJy.

In our late internal shock model, if we adopt the values $\epsilon_e = 0.4$, $\epsilon_B = 0.02$, $L_m = 10^{52}$ ergs s^{-1}, $\Gamma = 200$, $\Gamma_{\rm sh} = 1.6$, and $\delta t = 20$ s, then we find $\nu_m \sim 6.3 \times 10^{14}$ Hz, $\nu_a \sim 8.4 \times 10^{13}$ Hz, and $\nu_c \sim 1.2 \times 10^{12}$ Hz, so it is in the fast-cooling phase. Between ν_a and ν_m the spectrum takes the form $F_\nu \propto \nu^{-1/2}$, and at the observed frequency (3×10^{14} Hz) the flux is 49 mJy, which is quite consistent with the observation. In addition, with the values of ϵ_e and ϵ_B the Compton parameter $Y \simeq 4$, so the synchrotron photons will be Compton-scattered to high energy; the energy spectrum between 10^{16} and 10^{19} Hz is also $F_\nu \propto \nu^{-1/2}$, and we can estimate the flux at 1 keV to be about 0.06 mJy, which is also in good agreement with the observation.

2.2. *The Reverse-Shock Model*

After the internal-shock phase, as the fireball is decelerated by the circumburst medium, a pair of shocks usually develops (Mészáros & Rees 1997; Sari & Piran 1999; Kobayashi 2000). The early optical afterglow light curve is usually composed of contributions from both the forward shock (FS) and the reverse shock (RS). With this model, the very early optical/IR flash following GRBs 990123, 021211, 041219a, and 050525a can be well modeled if the physical parameters are quite different for the FS and RS (Fan et al. 2002; Zhang et al. 2003; Kumar & Panaitescu 2003; McMahon et al. 2004; Fan et al. 2005b; Blustin et al. 2006). For example, Fan et al. (2002) performed a detailed fit to the data on the optical flash of GRB 990123 and obtained $\epsilon_e^r = 4.7\epsilon_e^f = 0.6$ and $\epsilon_B^r = 400\epsilon_B^f = 0.4$, where the superscripts "r" and "f" represent the RS and FS, respectively.

Böer et al. (2005) found that both the optical flare and the gamma-ray burst of GRB 050904 were as energetic as those of GRB 990123 (in the rest frame of the GRBs). If the other parameters (including the initial Lorentz factor of the ejecta and the number density of the interstellar medium n) are similar for these two events, then the resultant shock parameters should be similar, too. So, it is very likely that in the current case the shock parameters of the FS and RS are also different.

Recently, we developed a code to calculate GRB afterglow light curves, including the FS and the RS emission components (Yan et al. 2005). In the current calculation, two novel effects have been taken into account. One is that in previous works, the Lorentz factor of the outflow, as well as the comoving number density of particles, was assumed to be constant. This may not be the case, since in the standard fireball model the gamma-ray burst is from the internal shocks. The detected gamma-ray light curve is so variable that the involved outflow may be variable, too (both the Lorentz factor and the particle number density). In order to model the optical plateau (Boër et al. 2005), and partly for convenience, in this work we assume that the outflow can be approximated as having two parts. Their bulk Lorentz factors, isotropic energies, and widths are $(\eta_{(1)}, E_{\rm iso(1)}, \Delta_{(1)})$ and $(\eta_{(2)}, E_{\rm iso(2)}, \Delta_{(2)})$, respectively. The other improvement is a more reliable calculation of the arrival time of the RS emission. We take the emission time of the first gamma-ray photon as our zero point of time. On the line of sight ($\theta = 0$), a gamma-ray photon γ_P arriving at t implies that the distance from the corresponding electron (i.e., point P, at which the bulk Lorentz factor is η) to the initial outflow front is $\sim ct/(1+z)$. The radial distance from the FS front to the central engine is R_P when the RS crosses point P. At that time, the separation between photon γ_P and point P is $\approx(1-\beta_\eta)R_P$, where $\beta_\eta = (1-\eta^{-2})^{1/2}$. Therefore, the arrival time of the RS emission from point P should be $t + (1+z)(1-\beta_\eta)R_P/c$. It is straightforward to extend this calculation to the case in which $\theta \neq 0$. It is found that the I-band flare of GRB 050904 can be well reproduced with the following parameters (see Fig. 1, *inset*): $\eta_{(1),2} = 380$, $E_{\rm iso(1),54} = 0.4$, $\Delta_{(1),12} = 1.3$, $\eta_{(2),2} = 800$, $E_{\rm iso(2),54} = 0.3$, $\Delta_{(2),12} = 0.7$, $n = 3$ cm^{-3}, $\epsilon_e^r = 0.6$, and $\epsilon_B^r = 0.4$. It is surprising to see that the resulting reverse-shock parameters are nearly the same as those for GRB 990123 (Fan et al. 2002).

Could the X-ray flare be from the RS, too? The answer is negative. First, as shown by Fan & Wei (2005), the decline of the X-ray emission of the RS cannot be steeper than $t^{-(2+p/2)}$, which is inconsistent with the observation. Secondly, now the reverse-shock region is significantly magnetized, so the RS emission in the X-ray band should also be dominated by synchrotron radiation. Thus, the X-ray emission should be an extension of the optical emission. However, the observation shows that the optical–to–X-ray emission cannot be described by a simple synchrotron spectrum (Boër et al. 2005). Therefore, the

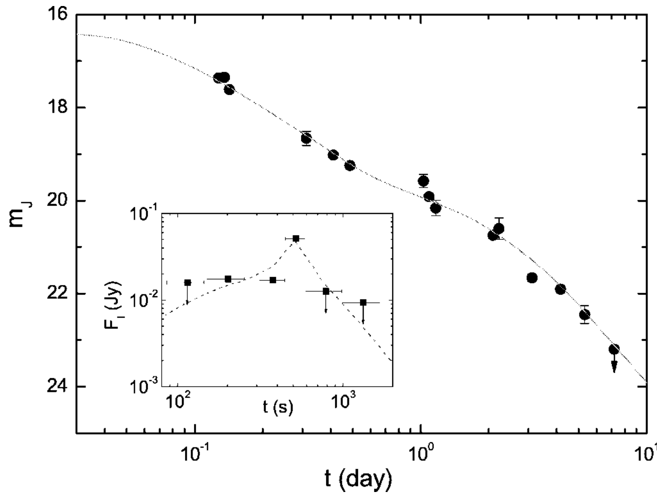

FIG. 1.—Modeling the *I*-band flare (*inset*) and the *J*-band afterglow of GRB 050904. In the inset, the *I*-band flare data (*squares*) are from Boër et al. (2005), and the dashed line is the theoretical light curve of the reverse-shock emission. The *J*-band afterglow data (*circles*) are from Haislip et al. (2005) and Tagliaferri et al. (2005). The solid line is the theoretical light curve of the *J*-band afterglow. [*See the electronic edition of the Journal for a color version of this figure.*]

X-ray flare accompanying the optical flare should be attributed to the activity of the central engine in the RS model.

3. FITS TO THE LATE *J*-BAND AFTERGLOW

Multiwavelength afterglow light curves of GRB 050904 have been detected, especially in the the *J* band (Haislip et al. 2005; Tagliaferri et al. 2005; references therein). Between ∼3 hr and 0.5 days after the burst, the fading of the afterglow can be described by a power law with index −1.36. After that time, the light curve flattens to a temporal index of −0.82. A break appears at time $t_b \simeq 2.6$ days, which suggests that the outflow may be a jet. In this Letter we pay more attention to the optical flattening. We note that at observer times $t \sim 10^4$–10^5 s there are strong X-ray flares (Cusumano et al. 2005; Price et al. 2005; Watson et al. 2005). Fan & Wei (2005) suggested that when the moderate relativistic outflow powering the X-ray flare caught up with the initial GRB ejecta, a flattening would occur in the long-wavelength afterglow light curve. In the calculation, we assume that between $t \sim 4 \times 10^4$ s and $t \sim 1.5$ days a significant amount of energy is injected into the decelerating GRB ejecta. Similarly to Zhang et al. (2005), the energy injection rate is taken to be $dE_{\rm inj}/[dt/(1+z)] = Ac^2(t/t_0)^{-1/2}$, where A is a constant. We set $A = 0$ when there is no energy injection. With energy injection, equation (8) of Huang et al. (2000) should be replaced by

$$d\gamma = \frac{(1-\gamma^2)dm + A(t/t_0)^{-1/2}[dt/(1+z)]}{M_{\rm ej} + \epsilon m + 2(1-\epsilon)\gamma m}, \qquad (5)$$

where γ is the bulk Lorentz factor of the GRB ejecta, $M_{\rm ej}$ is the rest mass of the initial GRB ejecta, m is the mass of the medium swept by the GRB ejecta (which is governed by $dm = 4\pi R^2 n m_p\, dR$, where m_p is the proton rest mass, $dR = \gamma[\gamma + (\gamma^2-1)^{1/2}]c\, dt/(1+z)$, and $\epsilon = x\epsilon_e$ is the radiation efficiency. With the dynamical evolution of the ejecta, it is straightforward to calculate its FS emission (e.g., Huang et al. 2000; Yan et al. 2005).

The fits to the *J*-band data (taken from Haislip et al. 2005 and Tagliaferri et al. 2005) are presented in Figure 1. It is found that the data can be well modeled with parameters $E_{\rm iso,54} = 0.7$, $n = 3$ cm^{-3}, $\epsilon_e^f = 0.15$, $\epsilon_B^f = 0.001$, $A = 7 \times 10^{49}$ ergs s^{-1}, $t_0 = 4 \times 10^4$ s, and a jet angle $\theta_j = 0.054$. Note that the value of θ_j is obtained by fitting the afterglow light curve, not from the simple analytic relation. Compared with the reverse-shock parameters derived in § 2.2, the shock parameters of the FS and the RS are quite different, as found for GRB 990123 (Fan et al. 2002; see also Zhang et al. 2003). The isotropic energy of the gamma rays is ∼5×10^{53} ergs and the derived $\theta_j = 0.054$, so the geometry-corrected energy should be ∼7×10^{50} ergs, which is typical for the GRBs detected by *BeppoSAX*, *HETE-2*, and *Swift*. In our treatment, the flattening is caused by the late energy injection. The total isotropic energy injected into the GRB ejecta is ∼6×10^{53} ergs.

4. DISCUSSION AND CONCLUSIONS

The optical flare that has been detected in GRB 050904 is as bright as the optical flash of GRB 990123 (in the rest frame of the bursts) and seems to have been accompanied by an X-ray flare (Boër et al. 2005). Here we explored two possible models to account for that observation. One is the “late internal shock model,” in which the optical flare is produced by synchrotron radiation from the electrons accelerated by the late internal shock and the X-ray flare is produced by the synchrotron self-Compton process.[3] The other is the external forward-reverse shock model, in which the optical flare is from the reverse shock’s emission and the X-ray flare is attributed to the central engine. We have shown that with the proper parameters, a bright optical flare can appear in both models.

In the forward-reverse shock scenario and with late-time energy injection, we have modeled the optical flare as well as the late *J*-band afterglow numerically. The resultant shock parameters for the forward and reverse shocks are $\epsilon_e^r = 4\epsilon_e^f = 0.6$ and $\epsilon_B^r = 400\epsilon_B^f = 0.4$, respectively. These are quite similar to the values found for GRB 990123 (Panaitescu & Kumar 2001; Fan et al. 2002), which is a natural result in view of the similarity between the two GRBs and their optical flares (in the rest frame of the bursts).

As for the reverse-shock emission, previous works have usually assumed that the physical parameters are uniform, thus greatly simplifying the calculation. In reality, the observed gamma-ray emission light curve is quite variable, so it is very likely that the involved outflow would be also variable. We note that if the parameters were uniform, then before the peak time the flux would rise quickly, which cannot account for the observed plateau (Kobayashi 2000; Boër et al. 2005). For simplicity, here we divided the outflow into two parts. We expect that a real outflow will be nonuniform, so the parameters should have a continuous distribution within the shell, but the calculation is complicated.

Although both the late internal shock model and the reverse-shock emission can account for the observed optical flash and the X-ray flare, we favor the former, since in this model the optical flash and the X-ray flare have the same origin, which provides a natural explanation of their temporal coincidence. In the late internal shock model, it is required that, after the prompt γ-ray burst phase, the central engine is able to restart. Recently, two models have been proposed for the production

[3] However, in some cases the synchrotron emission may peak in the keV energy band; then the inverse Compton component would peak at GeV energies (unless the outflow is highly magnetized, as suggested by Fan et al. 2005a), which may be detectable by the upcoming *Gamma-Ray Large Area Space Telescope*. This possibility will be discussed in greater detail elsewhere.

of late energy injection (King et al. 2005; Perna et al. 2006; MacFadyen et al. [2005] have proposed another model to account for the X-ray flares in short GRBs). In the reverse-shock model, on the other hand, the temporal coincidence of the optical flash and the X-ray flare can only be regarded as fortuitous. In addition, we note that in the late internal shock model the typical synchrotron radiation frequency strongly depends on the parameters, such as Γ, $\Gamma_{\rm sh}$, L_m, and δt, and for different burst sources it is natural that these parameters would be different, so we expect that the late internal shock model can not only produce the optical or X-ray flare but also produce a flare at other wavelengths, such as the ultraviolet or infrared. Meanwhile, we predict that the synchrotron self-Compton process may produce emission at high (nearly GeV) energies.

Despite its high redshift, the optical afterglow of GRB 050904 is not peculiar with respect to other GRBs. Recently, Zhang et al. (2005) and Nousek et al. (2006) analyzed the X-ray afterglows of many GRBs, and they found that some features (X-ray flares, the flattening of the light curve, a late-time break) occurred in a good fraction of GRBs. These features are consistent with the afterglow of GRB 050904. We suggest that the progenitor of GRB 050904 may be not very different from that of other GRBs in view of these similarities.

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